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ENHANCEMENT OF TRANSONIC AIRFOIL PERFORMANCE USING PULSED JETS FOR SEPARATION CONTROL

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14. ABSTRACT

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Abstract

Selected active and passive flow control devices have been investigated for their possible improvements to transonic airfoil performance. These investigations are part of co-operative effort between the US's Air Force Research Laboratory (AFRL) and the UK's Defense Evaluation & Research Agency (DERA) to explore flow control concepts. In particular, this manuscript reports on an experimental demonstration of pulsed vortex generator jets (PVGJs) conducted in DERA's High Speed Tunnel in Bedford. The primary goal of this test was to demonstrate the effectiveness of using PVGJs to suppress shock-induced separation on a transonic airfoil. It had yet to be demonstrated that this control technique would result in a net performance improvement. The influence of pulsing frequency on performance was evaluated over a range of lift conditions. The experiments were conducted at Mach numbers from 0.67 to 0.71, yielding chord Reynolds numbers of about 19 million.

Nomenclature

$\bar{c}$	= airfoil chord length
C_D	= airfoil section drag coefficient
C_L	= airfoil section lift coefficient
C_m	= airfoil section moment coefficient
C_N	= airfoil section normal force coefficient
C_p	= pressure coefficient
d_{jet}	= diameter of the jet
F^+	= dimensionless frequency, $f\ell / U_\infty$
h	= reference height or height of fixed solid device
ℓ	= reference length
L/D	= lift-to-drag ratio
m	= mass
$\dot{m}$	= $dm/dt = m_{,t}$ = mass flow rate into the system
M	= Mach number
P	= static pressure
P_t	= total pressure
q	= dynamic pressure, $\frac{1}{2}\rho U^2$
Re	= freestream unit Reynolds number, $\rho_\infty U_\infty \ell / \mu_\infty$
Re_c	= chord Reynolds number, $\rho_\infty u_\infty \bar{c} / \mu_\infty$
S	= reference area
T	= temperature
u^+	= inner turbulent velocity, u/u_τ; $u_\tau^2 = \tau_w/\rho_w$
U	= mean velocity vector
u,v,w	= mean Cartesian velocity components
VR	= pulse velocity ratio, $V_{jet,max}/V_\infty$
x,y,z	= Cartesian coordinates
y^+	= inner turbulent coordinate, yu_τ/ν; $u_\tau^2 = \tau_w/\rho_w$
α	= airfoil incidence or angle-of-attack (degrees)
Δ	= pulse duty cycle
ν	= molecular kinematic viscosity, μ/ρ
ρ	= density
β_{VG}	= skew angle of jet or VG to freestream.
μ	= viscosity

Subscripts

jet	= jet condition or property
t	= total condition
w	= wall condition
∞	= free stream condition
0	= reference condition

1 Introduction

This research was conducted as part of a co-operative program between AFRL and the UK's Defense Evaluation and Research Agency (DERA). The objective of this collaboration has been to develop and demonstrate each party's sub-boundary layer flow control devices for future application on military and civil aircraft wings. While past studies at DERA have been centered on passive solid sub-boundary layer flow control devices[1,2,3], recent efforts at AFRL have been directed at active devices. The effort presented here was also part of an AFRL program aimed at improving the aerodynamic performance of military transport aircraft. This program has been aimed at developing technologies to enable future transports for the imminent 'Global Mobility' missions identified in the Air Force's *New World Vistas* (NWV) report.[4] This report advocates the research of advanced wing concepts that could pay off in significantly

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higher aircraft efficiencies. It is our belief that emerging technologies in active flow control may provide significant improvements in aircraft performance beyond the NWV goals, enabling new classes of aircraft, and new mission capabilities. Therefore, many efforts are being directed at developing and validating flow control methods for future applications on military aircraft wings.

Flow control development, device characterization, and integration assessment have become an important part of the Aeronautical Sciences Division's technical activities in flow control.[5,6] One objective of these activities is to develop and demonstrate computational tools and analytical methods required to design systems employing active flow control. This will probably require the use of analytical models for flow control devices that are founded on a combination of theoretical, experimental, and numerical investigations. One such investigation was undertaken in an earlier AFRL-DERA collaboration[7,8] where the flowfields around several active and passive flow control devices were surveyed. These experiments were directed at establishing an experimental database to use in modeling and analysis efforts, and also to use as a baseline for extended computational fluid dynamics analyses.

1.1 Boundary Layer Separation Control

Separation control devices are used routinely on military, commercial, and general-aviation aircraft. The most common of these devices is the solid-vane vortex generator (VG), typically used on wings to improve flight characteristics during off-design operation. These surface-mounted VGs create vortices that travel over the upper surface bringing high-energy fluid from the free-stream into the boundary layer. This energizes the boundary layer making it much more resistant to flow separation. The separation point is forced further aft along the wing chord, or even eliminated. One operational benefit is that separation is delayed to higher angles of attack, increasing the maximum available lift for maneuver, or permitting flight at lower airspeeds with improved control authority.

While these devices are popular for the aerodynamic and handling improvements they provide, they are generally not an optimal solution. This is primarily due to their unalterable nature once they are installed, and their associated parasite drag. It would be advantageous to have a system that has the same benefits, but could be "deactivated" while not in use. Better yet would be a system that could be actively "tuned" to the specific operating condition to overcome whatever performance deficiency it is experiencing. One might also contemplate using separation to an advantage, if it could be reliably and predictably controlled in a closed-loop manner. These considerations have led to the development of numerous varieties of pneumatic VGs.

1.2 Transonic Airfoil Performance Improvement

This paper discusses a slightly different application that is also based fundamentally on the control of separation. As a transonic aircraft increases its cruise Mach number, shocks develop on the airfoil's upper surface. This shock becomes much stronger as the aircraft increases Mach number, escalating the associated wave drag. In addition, the pressure jump through the shock imprints itself on the boundary layer. This adverse pressure gradient ultimately leads to the boundary layer's separation. At this point, the lift produced by the airfoil is dramatically decreased, requiring the aircraft to fly at an increased angle of attack, and produce much more induced drag. Either weakening the shock or suppressing the shock-induced separation could greatly improve cruise performance. However, methods to reduce one of these drag increments often has an adverse effect on the other.[9,10] The challenge has been to identify and control methods for transonic wings that reduce the total cruise drag, considering both wave drag and shock-induced separation effects.

1.3 Related Experiments

The effects of selected solid sub-boundary layer vortex generators (SBVGs) on the same airfoil are presented in the companion paper of *Ashill, Fulker, and Hackett*[11]. In these experiments, solid sub-boundary layer vortex generators were placed as an array at the 46.5% chord location (approximately 70 device heights upstream of the presumed position of the shock). Two types of SBVGs were tested. The first type consisted of pairs of counter-rotating vanes spaced at the trailing edge by one height, and the second type was a line of forwards facing wedges. Each element of the second geometry is equivalent to a pair counter-rotating delta vanes joined at the trailing edges, and filled in the interior. The height of both devices was 0.76mm (equal to the boundary-layer displacement thickness expected at the position of the devices). The lateral spacing between each device (or vane pair) in the array was 12 device heights.

The shapes, heights, and spacing of these devices were determined based on previous studies[12] conducted in a low-speed boundary layer tunnel on a separation bump. This earlier study had indicated that properly designed and positioned SBVGs might provide improved maneuver performance of aircraft at high subsonic speeds.

These types of SBVG devices work by generating "trailing vorticity" which brings high-energy fluid from the free-stream into the boundary layer much like traditional vortex generators. This leads to a fuller boundary layer velocity profile that is resistant to flow separation. Air jets also create trailing streamwise vorticity[18], but may also be pulsed to interact with the natural dynamic instabilities of the flow and greatly increase the resistance to separation. This was the motivation for the investigation reported here.

1.4 Pulsed Vortex Generator Jets

The pulsed vortex generator jet (PVGJ) concept for separation control was initially based on a previously developed method of producing streamwise vortices using transverse air jets, usually called vortex generator jets (VGJs). Since first conceived in the early 50's[13,14], steady-blowing techniques have been studied extensively[15,16,17,18,19] and are still being investigated today[20,21,22,23]. Most of the recent investigations have been aimed at optimizing the jet orientations and orifice shapes for specific applications. In this method, steady jets are pitched to the surface and skewed to the freestream to generate vortices somewhat similar to those produced by solid VGs. Early research showed that blowing through discrete jets located near the leading edge on the upper surface of an airfoil could impede separation. This is achieved by energizing the boundary layer through turbulent mixing of the high-speed external fluid into the low-speed boundary layer fluid, causing an increase in the boundary layer momentum flux. It has been shown that this interaction causes the formation of longitudinal vortices similar to those produced by solid VGs, which are largely responsible for the mixing and increased resistance to separation. Johnston[24] has recently published a thorough review paper of the progress made in this area.

1.4.1 Early PVGJ Efforts

Pulsing the jet was first considered as a means to reduce the mass-flow requirements of the steady jet, while possibly enhancing the mixing process. The PVGJ concept has been developed in various places for several specific applications. Its developmental history at the Air Force Research Laboratory (AFRL) has primarily been aimed at separation control over wings and airfoils for enhanced maneuverability and off-design performance. Preliminary separation-control experiments were conducted under the Small Business Innovation Research program by McManus.[25] The primary objective of this program was to develop and test the PVGJ separation control system over a broad range of flight conditions on representative two- and three-dimensional aerodynamic surfaces. The aircraft application was control of the separation on a discontinuous leading edge flap.

Preliminary separation control experiments were conducted at low speeds on very simple flat plate "airfoil" with a flat 15° leading edge flap[26,27]. The effects of jet diameter and spacing were examined for single and counter-rotating jet pairs located on the flap. The effects of pulsing amplitude and frequency, as well as the jet diameter spacing, were also evaluated. The time-dependent flow characteristics at the jet exit were characterized, but other diagnostics were limited to mean surface pressure measurements on the flat plate and pressure surveys of the wake.

More low speed experiments were conducted on a NACA-4412 airfoil with a flat leading edge flap to determine optimum pulsed jet operating conditions for airfoil stall suppression[28]. In these experiments, PVGJs effectively delayed stall on airfoil over large range of leading edge flap deflection angles. Compressible flow experiments were also performed at free stream Mach numbers from 0.3-0.6 on an SP215 airfoil that was modified to 'bend' at $0.25\bar{c}$ to form a leading edge flap. Results again indicated significant aerodynamic improvements at high angle-of-attack ($\alpha > 12°$) by reducing or eliminating separation. Lift was increased by up to 21% at M=0.4, and by as much as 14% at M=0.5. Lift-to-drag ratio (L/D) was increased by up to 35%.

Finally, low-speed tests were performed on a 7% scale 'lambda-wing-body configuration' fitted with embedded pneumatic jet actuators near the wing leading edge[29]. In these experiments, blowing coefficients (C_μ) of 0.007 were typical. Effectiveness was demonstrated for a range of flap settings for high lift ($15° \leq \alpha \leq 40°$). The system increased the maximum lift coefficient by as much as 7% and L/D by up to 17%. It was also demonstrated that asymmetric use of the pulsed jets could be used to produce substantial roll moment that increased monotonically with pulse intensity. Experiments have since been conducted[30] to study the use of PVGJs for *dynamic* stall.

All of these early experiments, as well as the efforts of many others[31,32,33,34], have indicated that there is significant potential for pulsed jets and other oscillatory blowing techniques to suppress separation in a variety of environments. However, we have limited knowledge of how the time-dependent flowfield induced by the jet actually behaves, or how it interacts with the boundary layer to suppress separation more effectively than steady VGs, other than the flow visualizations of Johari & McManus[35]. In these experiments, effectiveness was quantified in terms of the degree of penetration of the jet fluid into the flow based on fluorescent dye and laser sheet visualizations.

1.4.2 Recent PVGJ Efforts

Most recently, the influence of a single PVGJ's jet velocity, pulsing frequency, and duty cycle on the mean characteristics of the flowfield on a turbulent boundary layer was assessed. The results of this experimental investigation of PVGJs in DERA's Boundary Layer Facility in Bedford have recently been reported in Reference 7. These experiments were part of an earlier co-operative effort between AFRL and DERA to survey flowfields created by numerous active and passive flow control devices. The experience and knowledge gained in these (and earlier) experiments was very useful when designing the PVGJ system for the transonic airfoil experiment that is the subject of this paper.

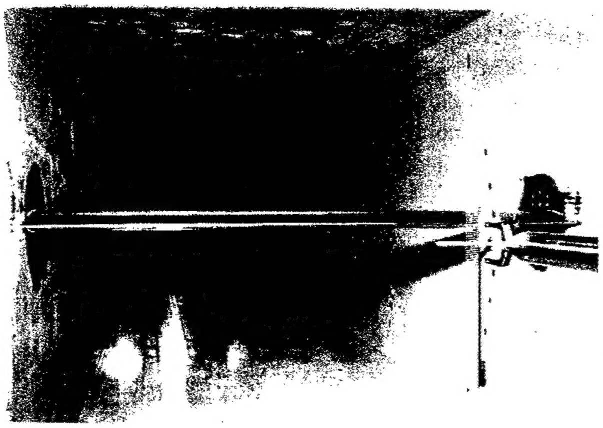


Figure 1: An airfoil in the DERA HST test section at Bedford with pressure wake rake behind.

2 Experimental Approach

The primary intent of this experiment was to demonstrate the use pulsed jets to suppress shock-induced separation on a transonic airfoil. While separation control was anticipated, the additional challenge was to demonstrate a benefit in terms of overall airfoil performance.

2.1 Testing Facility

The experiments summarized in this paper were conducted on an airfoil model mounted between the sidewalls of DERA's High-Speed Wind Tunnel (HST) at Bedford. This facility has an 8ft×8ft pressurized test section, capable of total pressures up to 4 bar, temperatures of 10 to 40 C, and Mach numbers from 0.13-0.87 and 1.3-2.5. The facility provides excellent flow quality and high Reynolds number capability (up to 10^7/m). It is equipped with a high-performance data acquisition system that allows steady & unsteady force measurement, momentum deficit drag measurement, electronic pressure scanning, and flow visualization.

2.2 Experimental Procedure

The tests were performed for Mach numbers between 0.67 and 0.71 at a Reynolds number based on chord length of 19×10^6. The performance of the control devices is assessed based on airfoil surface static pressure measurements and total pressures measured by a wake rake on the test section vertical plane of symmetry about 2 airfoil chord lengths downstream of the trailing edge.

The effectiveness of the flow control is assessed based on airfoil surface static pressure measurements, and section drag values based on the momentum deficit measured in the wake. This momentum deficit is determined from total pressure measurements made by a wake rake on the test section's vertical plane of symmetry. The rake is placed about two airfoil chord lengths downstream of the model's trailing edge. The surface pressure measurements are used to infer section pressure forces (lift and moment) on the airfoil.

Table 1: Tunnel test conditions.

Parameter	Value
M	.67, .68, .69, .70, .71
U_∞	218.3, 221.3, 224.3,227.3,230.2 m/s (716.3,726.1,735.8,745.6,755.2 ft/s)
q	57.7-62.2 kPa (1204-1300 lb/ft^2)
Re_c	$(18.9 \pm 0.1)\times10^6$
Re/ℓ	29.7×10^6 m^{-1} (9.06×10^6 ft^{-1})
P_t	2.40-2.45 atm
T_t	27.0-35.6 C

Table 2: Variations in PVGJ actuation parameters.

Parameter	Value
f(Hz)	50,150,200,300,400,500,573
$F^+/\ell = f/U_\infty$	.223-2.56 m^{-1} (.068-.78 ft^{-1})
$VR = U_{jet}/U_\infty$	2.63-2.77
V_{jet}	605 m/s (1986 ft/s)
M_{jet}	≈2.94
$dm/dt = \dot{m} = m,_t$ = mass flow rate	.010-.023 kg/sec (.022-.050 lbm/sec)
Δ = Duty cycle	≈40%

The measurement precision for various quantities is within the following ranges: C_D=±0.0001, C_N=±0.001, α=±0.005°, C_p=±0.001.

2.3 Wind Tunnel Model

The profile of the RAE 5243 (or the M2303 as it is more commonly known) airfoil used in the experiment (Figure 2) was designed to maintain natural laminar flow on the upper surface at a lift coefficient of 0.5 and a Mach number of 0.68. In the experiments, however, the boundary layer transition was fixed was tripped by small glass spheres glued to the surface at $0.05\bar{c}$ on the upper and lower surfaces. The wind tunnel model had a chord length of 0.635m, and had a maximum thickness to chord ratio ($t/\bar{c}$)of 14%. Airfoil ordinates are given in Ref. 9.

For this airfoil, the shock wave on the upper surface moves only a small distance with changes in Mach number and angle of incidence, remaining at about $0.55\bar{c}$. This is illustrated in Figure 3, where the surface pressure coefficient is shown the over a large range of incidence angles at the design Mach number. Figure 4 indicates the insensitivity of the shock location to Mach number (over the tested range) at just above the design lift condition. This characteristic makes the airfoil ideal for these demonstration experiments, where only one actuator location was feasible with affordable hardware that would allow exploration of many actuation frequencies.

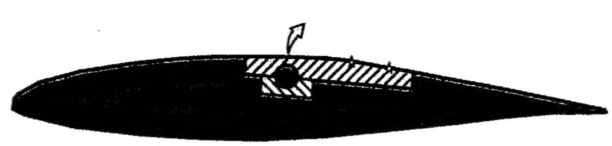


Figure 2: DERA M2303 airfoil profile. Location of the PVGJ insert and blowing location is indicated.

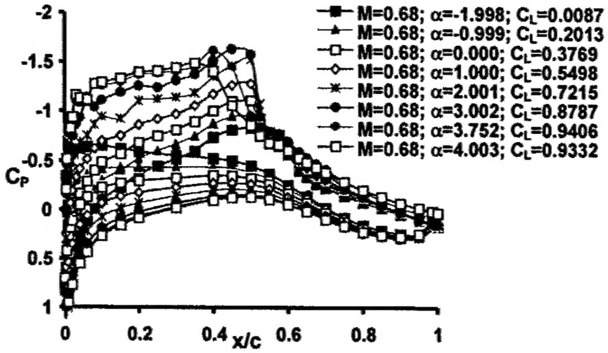


Figure 3: Surface pressures for M2303 airfoil at design Mach number and varying incidence.

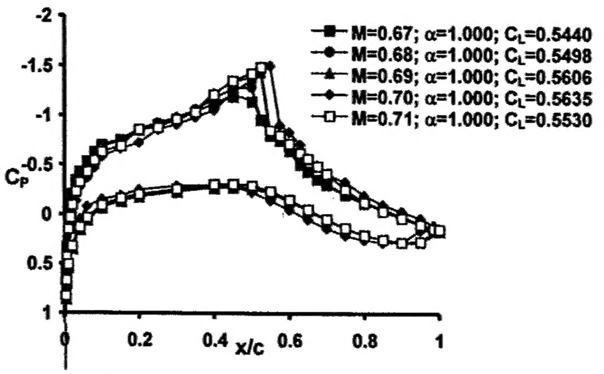


Figure 4: Surface pressures for M2303 airfoil at fixed incidence and varying Mach number.

2.4 Integration of the PVGJ Hardware

A major challenge in the project was designing and constructing a device capable of providing the required airflow at frequencies and duty cycles identified as critical in previous studies. It was also necessary to do this on a relatively small budget for experimental hardware. An approach was devised that allowed an existing 'insert' in the M2303 airfoil model's upper surface to be used to accommodate the control devices. This insert, which had been originally used for passive flow control methods at DERA, was modified to include a single spanwise row of PVGJs. The insert runs almost the entire 8-foot span of the airfoil, and covers the upper surface of the airfoil from about 0.37c to 0.68c. The insert was also re-instrumented with one streamwise and two spanwise rows of surface pressure taps for and assessing three-dimensional effects. Modifying the existing hardware saved resources, and helped to ensure compatibility when mating to the existing airfoil.

The resulting test article had a single row of 19 co-rotating jets distributed along a large portion of the airfoil span at about $0.465\bar{c}$ (Figure 5). This is at the same location as the trailing edges of the fixed devices tested in the companion[11] DERA experiments. This is about 0.06-$0.08\bar{c}$, or 38-51mm upstream of the expected shock

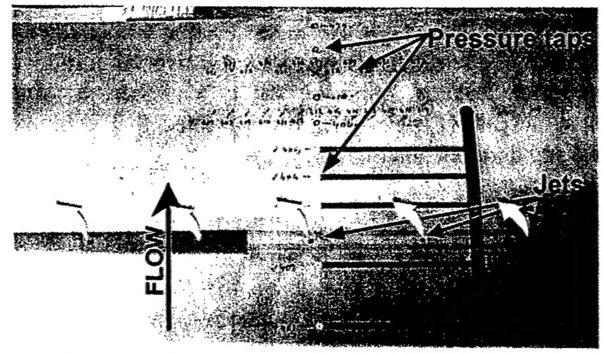


Figure 5: Outer surface of modified airfoil insert.

locations. The jets were spaced at 60mm intervals. This is equivalent to about $0.095\bar{c}$ length, which nearly is twice the spacing used by Wallace[14] in his early steady-jet experiments (discussed in Reference 16). It is also 30 times the jet's surface diameter (again, twice Wallace's factor), or 80 times the expected displacement thickness at the actuator location. Each jet was tilted 45° to the surface, and skewed 90° to the freestream (chord) direction.

The maximum instantaneous jet velocity was essentially fixed due to the nature of the supersonic jet geometry (provided the pressure was sufficient to produce the supersonic jet effect). The jets were designed to have an exit Mach number of 2.94. Each had a throat diameter of 1mm, and an exit diameter of 2mm. Assuming a perfect gas and an adiabatic expansion fixes the estimate of jet exit velocity at about 605m/s (1986ft/s). The jet pulse velocity ratio (U_{jet}/U_{∞}) then varies from 2.77 at M=0.67 to 2.63 at M=0.71. However, there is some uncertainty in the actual jet velocity that was produced, since measurements at the jet exit were not obtained. Borrowing empirical relationships from supersonic wind tunnel design[36], a total pressure of 10atm should be just enough to start a M=2.94 jet against the 1.75atm tunnel static pressure.

The jets were fed sharp pulses of high-pressure air. This was achieved by rotating slotted shaft inside a fixed "pillow block" (Figure 6). As the shaft was rotated, each time one of the eight shaft holes lined up with the hole in the pillow block, air was released to the jet. Between each pillow block, the shaft was slotted to allow air to freely flow into it. The shaft itself was a specialty item, and custom-machined by the manufacture. It had an outer diameter of ¾-inch, and was coated to form a bearing at each pillow block. Each air hole in the shaft had a 3mm diameter, setting the pulsing duty cycle of the system to something near 0.4.

The insert was also modified to form a sealed cavity underneath (inside the airfoil). This cavity housed the pulsing device described above, except for one end of the shaft where the rotation was supplied by a speed-

controlled Minarik brushless motor. The motor was mounted on the outside of the test section and coupled to the end of the shaft with a double universal joint. To minimize leakage from the cavity chamber, a "main plenum seal" (Figure 8) was constructed that contained two standard pneumatic rotary seals.

The mass flow rate to the system ($\dot{m}$) was measured and controlled by a regulator. While the line-pressure required to sustain the desired mean flow rate was recorded, it is not yet clear what the pressure and mass losses from the measurement locations to the jets were.

3 Results and Discussion

The results of the transonic flow control demonstration using PVGJs have been encouraging. Steady and pulsed blowing both increased C_L by eliminating shock-induced separation over a large range in angle of attack. Pressure distributions indicate a shock-induced separation bubble for the case without control. In most cases the addition of control either reduced the length of the separation bubble, or suppressed it entirely. However, at many conditions, steady blowing also increased the total airfoil drag. This drag increase seems to be largely mitigated by modulating the blowing in a pulsed manner. Below is a description of the baseline airfoil characteristics, followed by a discussion on the effects of steady and pulsed blowing parameters on airfoil performance at different Mach numbers and lift conditions.

3.1 Baseline Airfoil Characteristics

Although this same M2303 airfoil model had been tested several times in the past in this facility, it performance was reassessed for the present experiment at the relevant conditions. This allowed accurate condition matching to the actuated pulsed-jet experiments (Mach and Reynolds numbers), and prevented any differences due to updates in the data acquisition system or data reduction methods since the last time the airfoil was tested. These data were also used to preclude the possible passive effects of the inactive devices (holes in the airfoil surface). For this part of the experiment, the actuator shaft was rolled into a position that sealed the jet holes. The system flow rate was also monitored to assure that there was minimal leakage through the jets. The measured performance of the baseline airfoil is summarized in Figure 9.

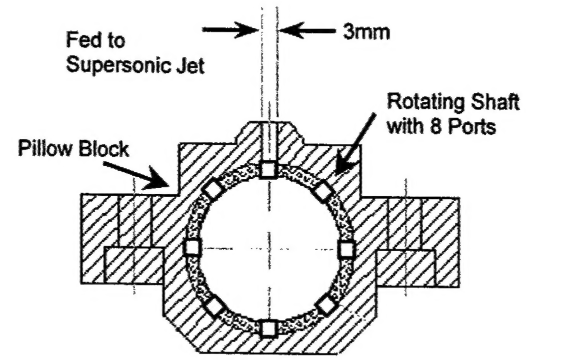


Figure 6: Detail of shaft and pillow block configuration.

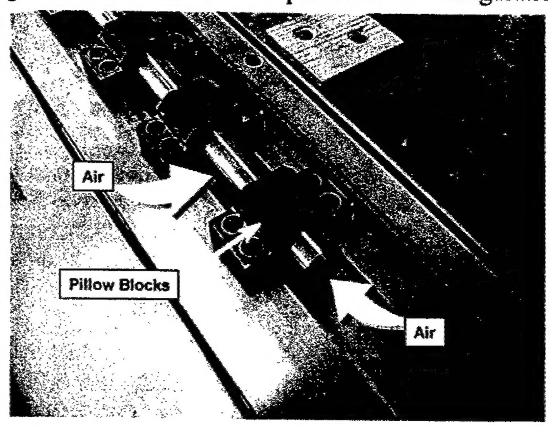


Figure 7: Pillow block air valves on insert underside.

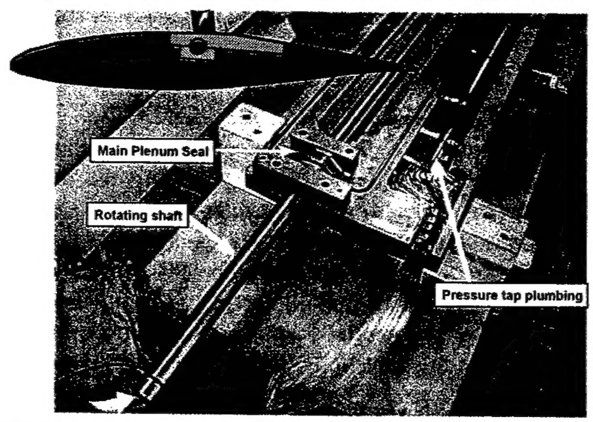
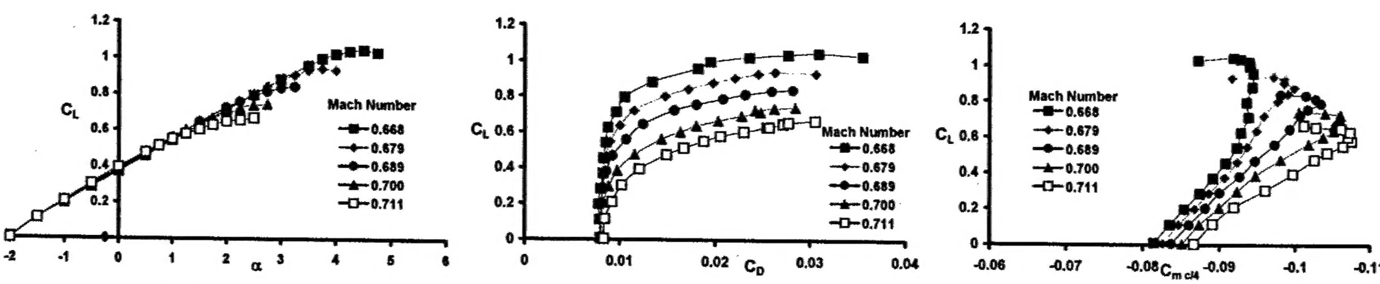


Figure 8: Underside of modified airfoil insert on the end where shaft was powered (motor not shown).



[a] Lift coefficient.

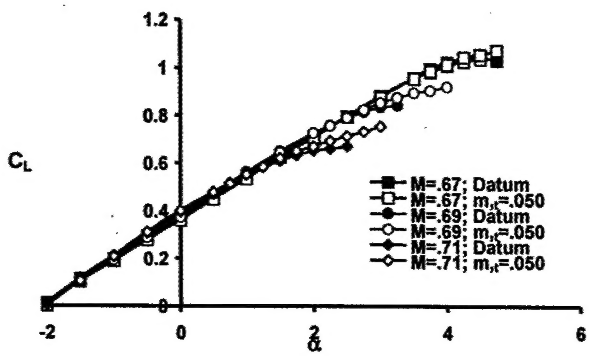
[b] Drag polar.

[c] Moment polar.

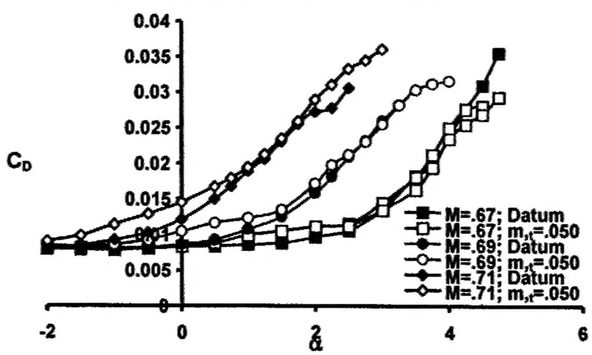
Figure 9: Baseline aerodynamic forces for test airfoil.

3.2 Steady Blowing

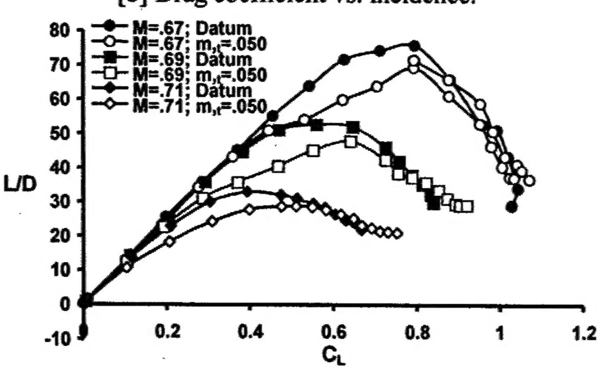
The effects of steady blowing were investigated at three Mach numbers (0.67,0.69,0.71) by sweeping through a range of incidence angles. This was done at a single mass flow rate of 0.05lb/sec, which required a very high line pressure, indicating significant losses. Steady blowing had a very small detrimental effect on lift at low incidence, which continued to higher incidences at the lower Mach number. However, it had a large favorable effect at high incidence (Figure 10[a]). This effect was seen at all Mach numbers tested, but became larger with increasing Mach number. Note that only the M=.67 case with no control was tested *through* maximum lift.



[a] Lift coefficient vs. incidence.



[b] Drag coefficient vs. incidence.

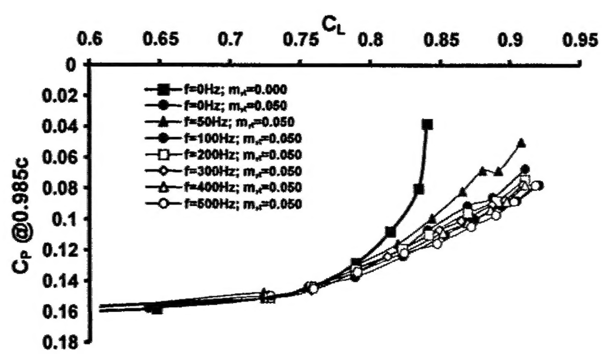


[c] L/D vs. lift coefficient.

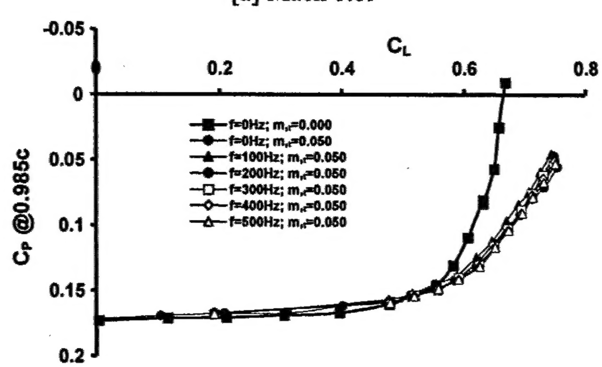
Figure 10: Effect of steady blowing at $\dot{m}$=0.50 lb/sec on airfoil performance.

While the steady blowing often increased the lift coefficient at a given incidence angle, it also increased the total airfoil drag. This is especially true at low incidence and high Mach number (Figure 10[b]). The ultimate result is a significant decrease in airfoil performance (L/D) at lower lift conditions (Figure 10[c]). The only benefits seen are the increase in $C_{L\max}$ and extension of the sustained maneuver performance to higher loading.

Another indicator that separation is being suppressed can be found in the surface pressure experienced on the upper surface after the shock. Looking at the surface pressures for the uncontrolled case at the design condition in Figure 3, we see that the upper surface trailing edge pressure remains about constant (at C_p=.17) for most lift conditions. However, the pressure aft of the shock begins to diverge quickly as the airfoil incidence is increased above about 2.5° (where C_L≈.8). Above this point, separation quickly becomes evident, and causes the shock to move forward from its otherwise unwavering location. This behavior is observed at all transonic conditions. When shock induced or trailing-edge separations occur, the pressure coefficient at the trailing edge location sharply rises with increased incidence (Figure 11). However, the steady jet control greatly delays the C_p drop associated with separation to higher lift conditions, and reduces the rate at which the pressure diverges with lift (dC_p/dC_L). The pulsed-blowing cases are discussed below.

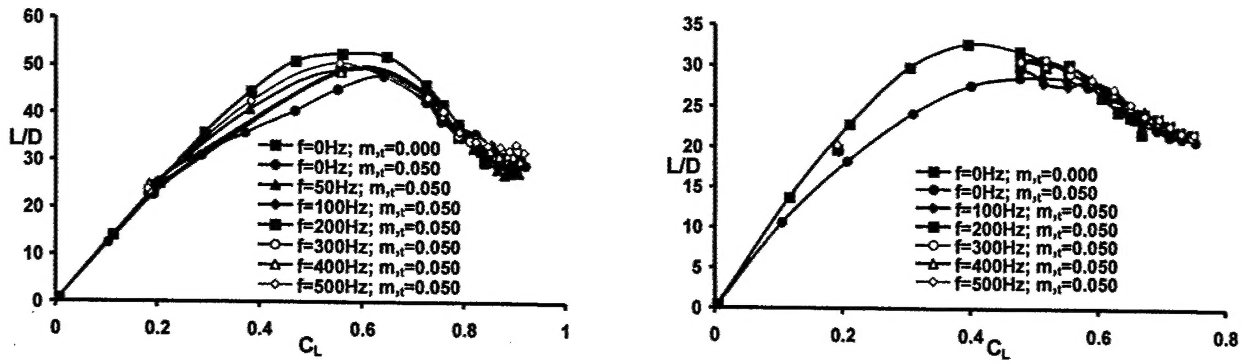


[a] Mach 0.69



[b] Mach 0.71

Figure 11: Effect of steady and pulsed blowing on the upper surface pressure coefficient at 0.985 $\bar{c}$.



[a] M=0.69 [b] M=0.71

Figure 12: Effect of pulsing frequency on airfoil performance at $\dot{m}$ =0.50 lb/sec.

3.3 Pulsed Blowing

Pulsing experiments were only conducted at the two higher Mach numbers. While data were obtained at other mass flow rates, the results obtained at the highest mass flow rate of 0.050 lb/sec are the focus of this analysis.

Pulsed blowing increased C_L and eliminated shock induced separation at high loading in a similar manner to steady blowing. However, the effect on the drag was significantly less detrimental. In particular, the drag increase experienced with steady blowing seems to be largely mitigated by modulating the blowing in a pulsed manner. This results in an overall increase in L/D over a large range of high-lift conditions, even as compared to steady blowing at the same mass flow rate (Figure 12).

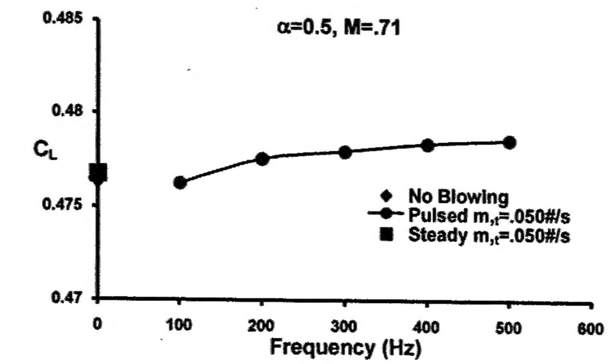
Differences in frequency appear to have only mild effects on the lift improvement of the airfoil due to pulsed blowing. This can be seen in the trailing edge pressures of Figure 11, where only the very low frequency (f=50Hz) case falls perceptibly out of line with the rest of the pulsed and steady cases. Still, the pulsing frequency does appear to have a significant influence on the overall airfoil performance due to its effect on the airfoil drag.

3.3.1 Effects on Airfoil Performance

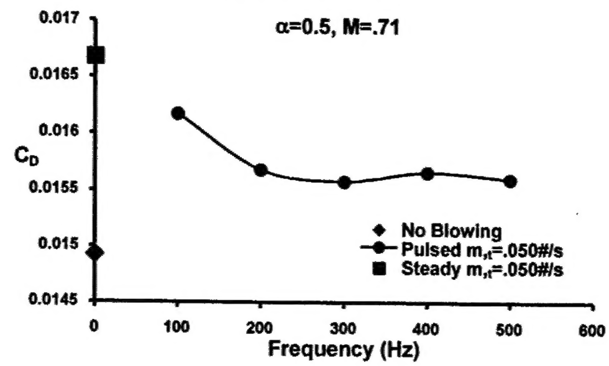
It is constructive to look at two specific cases for a given Mach number. The first is at an incidence when the airfoil is near its maximum L/D (cruise) condition, and the second is at the highest incidence tested in both uncontrolled and controlled configurations.

3.3.1.1 Near Cruise Conditions

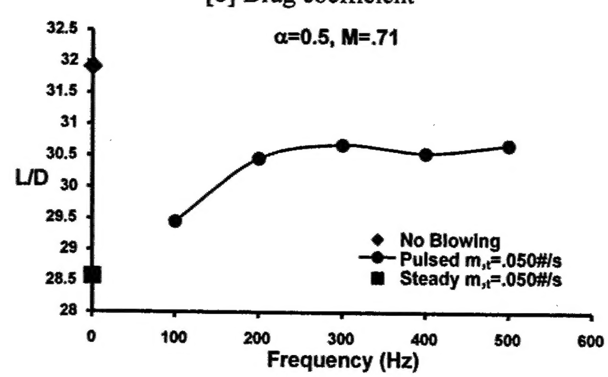
The reduction in $L/D_{\max}$ due to steady blowing was greatly reduced by pulsing. The L/D was even slightly increased above the uncontrolled case at one low lift condition (see C_L=0.2 in Figure 12[a]). Figure 13 illustrates the effects of frequency at a typical cruise loading condition (α=5°, C_L≈0.48) and a Mach number of 0.71. Here, the effects of pulsed blowing on C_L, C_D, and L/D are shown as a function of frequency. It is clearly seen that the influence of pulsing is related mostly to drag, and that the effect is only dependent on pulsing



[a] Lift coefficient



[b] Drag coefficient



[c] Lift-to-drag ratio

Figure 13: Effect of steady and pulsed blowing frequency on airfoil properties at M=0.71 & α=0.5°.

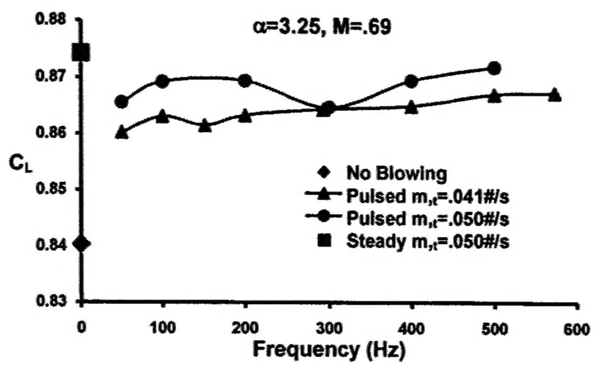
frequency below $f \approx 200$Hz. Sensitivities to blowing and pulsed blowing are very similar at Mach number 0.69.

It should be noted that for all cases tested, the airfoil never experienced an increase in its maximum *L/D* due to any type of blowing. No conclusive statement should be made to this effect however, since it was not the focus of the experiment and very little data were obtained near this condition.

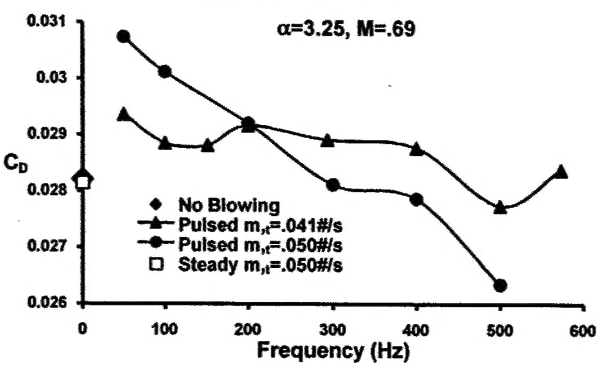
3.3.1.2 At High-Lift Conditions

Again, the lift enhancement provided by blowing is much stronger at high lift conditions but is still relatively independent of pulsing frequency. The effects of pulsed blowing frequency on C_L, C_D, and *L/D* are shown for high-loading conditions in Figure 14 and Figure 15 for Mach numbers of 0.69 and 0.71, respectively. Note that at a Mach number of 0.69, the high lift condition was tested at two different mass flow rates.

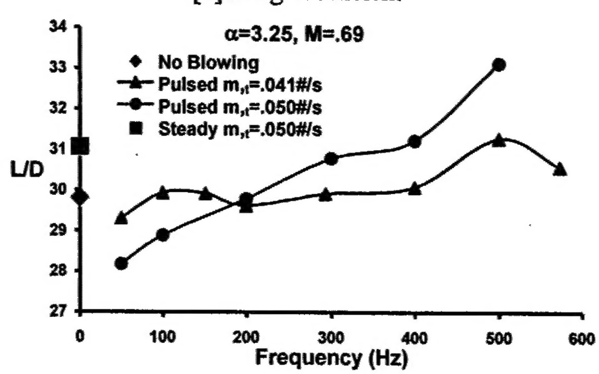
In contrast to the lower lift conditions, the pulsing frequency has a very strong influence on drag, even to the point of reducing drag very high frequencies (Figure 14[b). The combination of increased lift and decreased drag produces a significant performance benefit at these conditions, especially for higher frequency pulsed blowing, in comparison to both the uncontrolled and steady-blowing cases.



[a] Lift coefficient

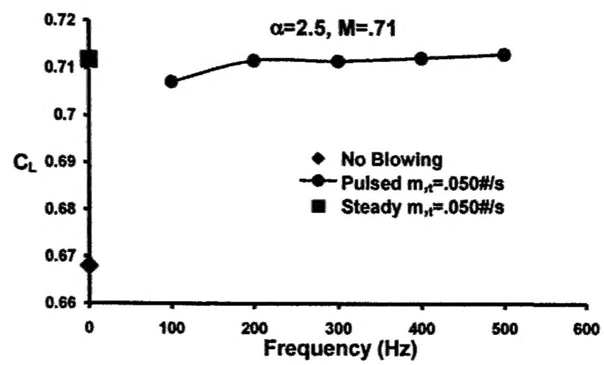


[b] Drag coefficient

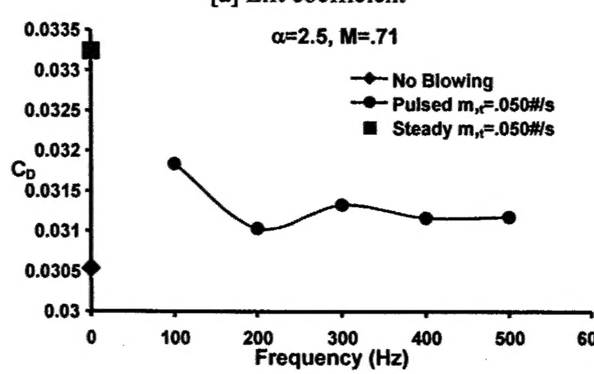


[c] Lift-to-drag ratio

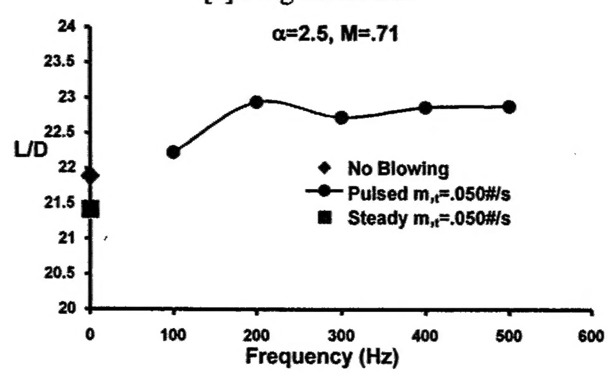
Figure 14: Effect of steady and pulsed blowing frequency on airfoil properties at M=0.69 & α=3.25°.



[a] Lift coefficient

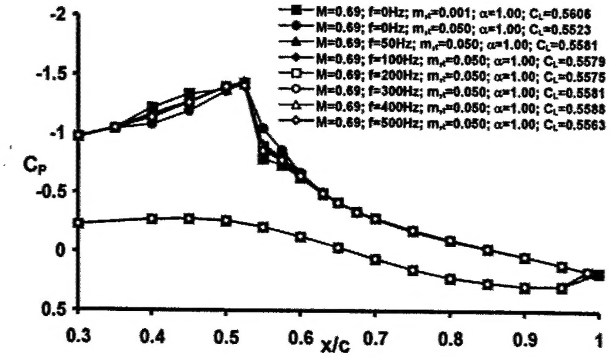


[b] Drag coefficient

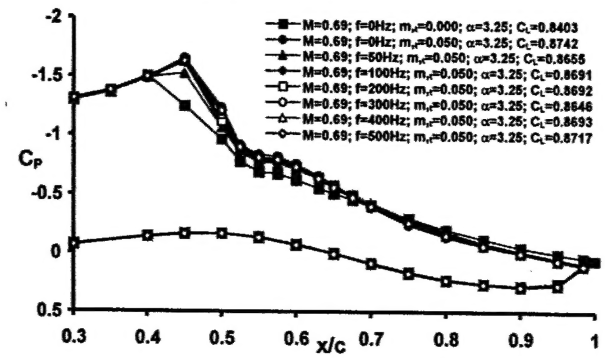


[c] Lift-to-drag ratio

Figure 15: Effect of steady and pulsed blowing frequency on airfoil properties at M=0.71 & α=2.5°.

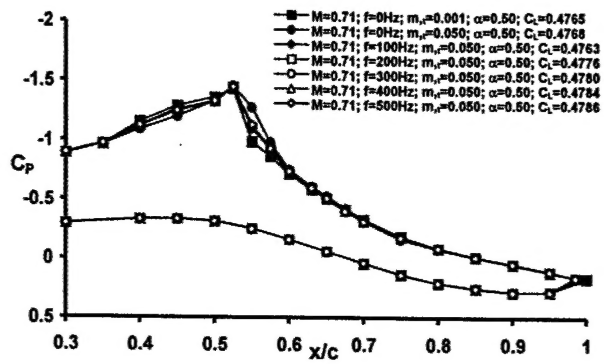


[a] M=0.69, α=1.0°

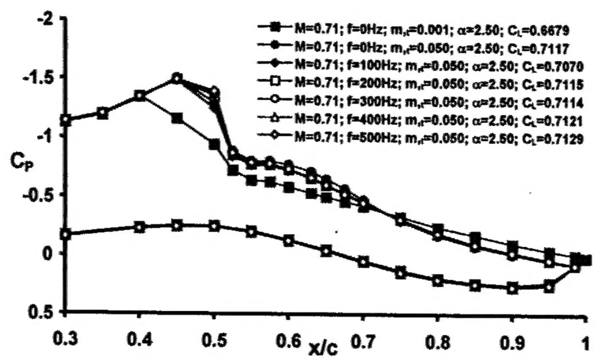


[b] M=0.69, α=3.25°

Figure 16: Surface pressure coefficient measurements.



[a] M=0.71, α=0.5°



[b] M=0.71, α=2.5°

Figure 17: Surface pressure coefficient measurements.

3.3.2 Effects on Surface Pressures

The influence of PVGJ control on the aerodynamic forces can be understood more thoroughly by examining the surface pressures at specific conditions.

The control was seen to have some effect on the surface pressures throughout the conditions tested. However, at low incidences where the uncontrolled airfoil does not exhibit separation, the control's influence appears to be weak and local (Figure 16[a] & Figure 17[a]). That is, pressure changes are only indicated in the region very near the control and shock. The flow upstream of the shock (and even upstream of the jets located at $0.47\bar{c}$) was altered in a way that increased the surface pressure. This appears to weaken the shock, and results in more suction being retained in the region just behind the shock. These effects are greatest for steady blowing, and about half as strong for all of the pulsed cases. Very similar effects are seen at both Mach numbers, but to a higher degree at the lower Mach number.

At high lift conditions, where the stronger shock provokes separation, the control's impact is much more global (Figure 16[b] & Figure 17[b]). The surface suction is significantly increased over a very short distance upstream of the shock. The increased suction is also very pronounced downstream of the shock. Also, the pressure fully recovers by the trailing edge, indicating that the separation is completely eliminated. While the separation control is complete at both Mach numbers, the suction increases appear more prevalently at the higher Mach number. While the influence of frequency on the surface pressures is mild, control at the higher frequencies approach the effectiveness of steady blowing. As discussed earlier, the true benefit of pulsing the jet at high lift conditions is seen in the reduction of drag.

4 Summary & Concluding Remarks

The results of the transonic flow control demonstration using PVGJs have been encouraging. Steady and pulsed blowing both increased C_L by eliminating shock-induced separation experienced at high lift conditions. This effect is consistent with that observed by earlier by early steady-jet researchers that are discussed in Reference 16. However, at many conditions, steady blowing also increased the total airfoil drag, resulting in a lower ratio. This drag increase appears to be largely mitigated by modulating the blowing in a pulsed manner.

At cruise lift conditions, the results did not improve much above a moderate frequency, and were never significantly better (in terms of L/D) than for the uncontrolled case. At high-lift conditions, the lift was substantially augmented by steady blowing and pulsed blowing at all frequencies. This was apparently due to the complete suppression of the shock-induced separation. The results were best at the

highest frequencies tested, where significant lift enhancement and *L/D* improvements were seen at all Mach numbers. The pulsed blowing becomes most effective at the higher Mach numbers where shock induced separation is more pronounced on the uncontrolled airfoil. Here, *L/D* improvements were seen at all frequencies. Near the design Mach number at high-lift, only pulsing at the higher frequencies reduced the substantial increase in drag experienced with steady blowing and resulted in an overall increase in *L/D*. This resulted in an overall increase in *L/D* over a large range of high-lift conditions.

It is concluded that if methods become available to mechanize pulsed blowing in an efficient and simple way, it could have play an important role in controlling shock induced separations on airfoils.

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